BNL LHC Dipole Conceptual Design Review

July 16, 1998

Introduction and Summary

The review was conducted at BNL on July 16, 1998 by a committee consisting of Jim Strait (Fermilab, US LHC Project Office), Phil Pfund (Fermilab, US LHC Project Office), Jim Kerby (Fermilab), Ranko Ostojic (CERN) and Steve Gourlay (LBNL).

This conceptual design review covered all of the dipoles that BNL will provide for the LHC, which are:

D1	single aperture interaction region beam separation dipole,
D2	twin aperture interaction region beam separation dipole,
D3a/b	twin aperture RF region beam separation dipoles of two different aperture spacings made of two cold masses in one cryostat,
D4a/b	twin aperture RF region beam separation dipoles of two different aperture spacings (one cold mass).

The purpose of the review was to evaluate for each magnet type and for the program as a whole if the specifications and requirements (magnetic, cryogenic, physical, interface, etc.) are adequately defined, if the chosen designs are likely to meet the requirements in a cost-effective way, if the design aspects requiring prototype construction or other R&D have been properly identified and if the planned R&D program is adequate to address these issues. The primary focus was to determine what issues needed to be resolved prior to completing the detailed design of prototypes of the D4b type. (D4a and D2 are of a very similar design, and D1 and D3, whose cold masses are only slightly modified from the RHIC design, do not require prototypes.) The review also provided a preview of the cryostat and cooling system designs which are in an earlier stage of development than the cold mass. This report will first discuss the issues raised organized by topic, and then summarize with a set of action items. Action items that need to be addressed before the final design and construction of the D4 prototypes will be distinguished from those that should be addressed before the final design is completed for the production magnets.

Overall the committee felt that the designs presented were very good, quite mature for this stage of the project. The magnets seem very likely to meet the magnetic field strength and field quality requirements and appear to be straightforward to manufacture, as they either are slightly modified RHIC magnets, or are of designs which are direct evolutions from RHIC magnets. The main concerns raised are related to the cooling scheme, the high current buses that pass through the magnets, and interfaces to other magnets or cryogenic and power feed boxes. These issues impinge on the decision as to whether to proceed with the prototypes, the main focus of this review, in that they affect the size and placement of features in the yoke, which in turn affect field quality. The committee recommends that BNL proceed directly to complete the detailed design of the prototypes, procure the parts and tooling required, and build them as soon as possible without waiting for resolution of all of the questions that will determine the details of the yoke design. However, it also recommends that answers to these questions be pursued vigorously and that the final design of the yoke be delayed as long as possible without holding up the schedule for the completion of the first prototype, with the goal of making the yoke used in the prototypes as close to the final design as possible. If all issues cannot be settled in time, the yoke die should be designed to allow straightforward modification as necessary.

Other questions and issues were raised, which, however, should not affect the prototype program directly. These need to be addressed before the final designs are made of the magnets to be installed in the LHC.

Magnet Parameters

The operating parameters, in particular the operating field of the various dipoles which are not all the same, were not completely presented. Working with CERN, BNL needs to identify the operating parameters for each of the dipoles, including minimum (injection) and maximum operating fields. For the maximum current the values for the nominal LHC energy of 7 TeV (corresponding to 8.33 T in the main dipoles) and for the ultimate 7.56 Tev (9 T in the main dipoles) should be identified. BNL should also specify the maximum field which can be achieved in each dipole type with adequate quench margin and sufficient field quality to maintain the required dynamic aperture of the LHC.

In the present LHC design, D3 and D4 are powered in series with a trim power supply on Ring 2 on both magnets. However, since in the proposed design D3 and D4 have different transfer function, BNL needs to specify the power scheme, including the maximum trim current required to match the D3 and D4 strengths.

To minimize the number of dipole correctors required in the interaction regions, D2 will be used as part of the steering system. The strength of the standard correctors replaced by this scheme is 2.5 Tm, corresponding to about 0.26 T in D2 at 7 TeV, and 0.55 Tm at injection, corresponding to about 0.06 T in D2. Thus the operating fields in the two apertures may differ by up to these amounts. BNL should evaluate the impact on field quality of asymmetric powering at injection and full energy by up to 1.5 times the nominal amounts given above.

Cable Parameters

The magnet program relies heavily on duplicating, as much as possible, the RHIC design. Therefore it is very important to verify that substituting SSC strand will produce cable that does not significantly differ from expectations. The SSC strand has lower Cu/SC ratio, which yields a larger superconductor volume, and has half-hard as opposed to full-hard copper. In addition, it appears that there may be wire from several manufacturers to make the cable. The parameters of the cables made from the different candidate wire samples should be determined as soon as possible, so that the impact on the coil parameters and the need to sort coils by wire vendor can be evaluated. One potentially important difference from RHIC coils is the expected smaller shrinkage of the conductor following coil curing, which may be wire vendor dependent, but other parameters may be important as well.

If wire from two different vendors must be used, BNL should consider making the two prototypes out of conductor from the two different manufacturers to characterize their different behavior as fully as possible.

Coil and Cold Mass Design

Two different cold mass designs will be used, one which is a slightly modified RHIC dipole which requires no R&D, and a two-in-one magnet of a new design with independently collared coils, which requires the construction of two prototypes to prove the design. In both cases the coils are identical to RHIC coils, with the exception of the wire parameters noted above. Most of the cold mass design issues considered are related to the new two-in-one design.

The cold mass design presented looks very good, based on experience with RHIC dipoles and SSC dipoles, and the probability of success is high. Several issues remain to be addressed, however, before the design can be finalized. Chief among these is related to the size and placement of the slots for the high current buses for the main dipole and quadrupole circuits which must pass through the D4s. BNL is considering building and installing buses of their own design, but has not yet discussed this option with CERN. With the plan to cool the magnets in a static bath of saturated liquid, there is a risk that the buses may not be bathed in liquid at the up-hill end of the magnet if they are located in the upper bus slots, and maybe even if they pass through the upper pipes in a standard LHC interconnect. For the moment BNL does not have enough information about the CERN bus or interconnect, nor enough understanding of how to cool and fill the magnets to determine where the bus slots can or must be located in the yoke. The field quality is somewhat sensitive to the bus hole locations. Under these circumstances BNL can choose to build the prototypes with the yoke design as presented now, with the expectation that the yoke will have to be redesigned later, or wait until the bus issues have been resolved to finalize the yoke design. The committee recommends that BNL delay the purchase of the yoke laminations for the prototypes as long as possible without delaying the schedule for the prototype assembly, while trying to solve the bus design questions in the available time. However, if the questions are not resolved, the prototype should be built with the yoke as close to the final design as possible, and the yoke design iterated later for the production magnets.

The ANSYS analysis of the twin-aperture magnets treated the problems of collar, end plate, and cold mass shell deflections and stresses. The collar analysis showed that a single collar key would work, but that a more conservative collar stress would result from two keys. The analysis clearly showed that the basic design is sound. However, a tolerance analysis still needs to be done to evaluate whether gaps could develop between the yoke and collar or between the yoke halves, and the effects of such gaps, if they could occur, should be evaluated. In particular, if yoke gaps are possible, a magnetic analysis should be done to understand if this matters. The tolerance analysis should allow for the possibility of different collared coil parameters between the two apertures. The effect of shell prestress due to weld shrinkage and cooldown should be included in the analysis.

The end volume design for the oblate cold mass has not been finalized yet. If it is made round at the minor diameter, then it may be possible to use the same castings that are used for the end domes of the main LHC dipoles.

Buses carrying the current for the main dipoles and quadrupoles in the adjacent arcs pass through the D4 dipoles. BNL could either use the same bus that CERN uses in the arc magnets or design their own bus that satisfies CERN specifications. The review committee believes that the first solution is preferable.

The quench protection system in the LHC, in which the eight apertures of the 2 D4s and 2 D3s are powered in series, relies on quench heaters, and the magnets are not separated by diodes.

BNL should work with CERN to evaluate the reliability of this system and the expected failure modes. Peak temperatures and voltages that might result from asymmetric action of the quench heaters should be evaluated.

Interfaces

Many interface details are not yet understood and it is likely that not all of them have been identified. Considerable effort needs to be put on identifying interfaces, and BNL should take the initiative to try to define the interface specifications. Good communication with CERN, Fermilab, and LBNL is crucial. Several interfaces that could have an effect on the magnet design are:

- D1 interface with the LBL DFB.
- D4 interfaces to the CERN DFB and to the Q7. This includes, as discussed above, the buses for main dipole and quadrupole circuits which pass through the D4s. Can both of these interconnects be made to look like standard arc magnet interconnects? Can CERN end dome castings be used?
- D3 interfaces to CERN DFB and to Q6. Are there buses for Q6 and Q5 passing though D3? (The beam separation of D3a and D3b being different, the bus bar slots will not be aligned to those in the DFB on the one side and in Q6 on the other, and in between the two magnets; a further complication for the interconnects).
- Bypass bus location, size and mounting in cryostat needs to be determined.
- High current buses for the main LHC dipoles and quads. Can BNL use their own version of main through-bus? Is it required for the use of CERN buses that they be installed in notches on the outside of yoke before shell welding, or can they be pulled in afterwards?
- Interfaces between BNL-built magnets, i.e. between D4a and D4b and between D3a and D3b. They should adhere to CERN standards wherever possible. If not, BNL specific tooling might be required.
- Interface of BNL-built magnets to the cryogenic transfer line. BNL needs to take the initiative in working with CERN to develop specifications for this interface and for the valve box that will feed the BNL dipoles.

As many as possible of these potential interfaces need to be identified and either they must be understood or allowances put into the design for later modifications. Making a set of electrical and cryogenic schematics for the RF straight section and for the D2 and the mating DFB and cryogenic service modules is a first step towards identifying and controlling interfaces. The development of these schematics must be done in close cooperation with responsible CERN engineers.

Field Quality

Generally it appears that the field quality of these magnets will be fully adequate for LHC. The one location where this is less straightforward is the D1 magnets in point 2, which will operate at low β^*, and therefore high β in D1 during heavy ion runs. Issues related to field quality include the following:

- SSC strand characteristics and persistent current effects -- how different are these from RHIC strand?
- D2's in points 1 and 5 will be operated at substantially lower current (150 A) than in RHIC (and than in points 2 and 8). The exact injection field should be identified and the field quality evaluated.
- Can the field quality of D1 at collision energy be improved by minor modifications to the yoke to control saturation effects better, or even by use of magnetic tuning shims within the body of the yoke, which would be "visible" at high field as the iron saturates?

Cryostat and cooling system

The cryostat design for all but the D1 represents a substantial departure from the RHIC design, and the proposed pool boiling liquid cooling design for all of the dipoles has not been widely used in accelerator magnets. Therefore the cryostat and cooling systems require substantial scrutiny. A problem is accommodating the slope variation in the tunnel and maintaining adequate helium levels in the vessel. D1 at point 2 represents the most severe case, and the next most severe is keeping the high current bus in D4 fully bathed in liquid. A system needs to be developed by BNL and CERN which minimizes the gas volume that accompanies the liquid fill, and analysis still needs to be done to ensure that the gas, which is introduced with the liquid at the low end of the magnet, can be adequately vented from the high end.

BNL should work closely with the cryogenics group at CERN to specify the requirements of the valve boxes and cryogenic service modules that feed their dipoles. For example, use of a counterflow heat exchanger upstream of the valve through which the 4.6 K, 3 bar liquid is expanded to 4.5K, 1.3 bar could substantially reduce the gas content of the fluid filling the magnets.

Beam or synchrotron radiation induced heating of the coil could result in local generation of gas bubbles within the coil. In the RHIC-type cold masses, the coil is surrounded by solid phenolic spacers, which have only occasional and small gaps between them. Are these gaps sufficient to vent gas formed within the coil? In the case of the collared coils in D2 and D4, the coils are wrapped with Kapton ground insulation. Can gas formed within the coil exit? Can this design ensure that in normal operation the coil will be bathed in liquid rather than gas? What is the minimal liquid level and gas fraction ensuring safe operation?

The number of posts for the two-in-one magnets needs to be determined, and the feasibility of using the surplus CERN prototype cryostat insertion fixture needs to be evaluated.

Alignment

The basic procedures and expected tolerances are well understood for D1, which is essentially a RHIC magnets, and alignment accuracy for the other magnets should be similar to that for the main LHC arc dipoles, since the same support structure will be used. However, few details were presented and not much thought has been put into alignment stability during shipment. Is CERN equipped to realign these magnets? Will they be able to interface to them on their test stand?

Schedule

The schedule presented allows at most a few months between the completion of testing of the prototypes and the beginning of assembly of the production twin-aperture dipoles. It also shows the purchase of materials for the production magnets being completed at the same time as the testing of the second prototype. Does this provide enough time to implement any design changes that might result from experience with the prototypes?

Action items to be addressed before completing the prototype detailed design

- Identify and tabulate operating parameters for each magnet type.
- Delay D4b prototype yoke final design as long as possible without delaying completion of the prototype. Use this time to define the interconnect requirements (especially those related to the bus) and the cooling system, with the goal being to set the cooling channel and bus slot locations as close to their final positions as possible.
- Verify parameters of cable made from wire from available SSC surplus. Evaluate -- by measurement and calculation -- effects of differences between SSC and RHIC strand on cable dimensions, coil modulus, cross-over resistance, magnetization, coil length, etc.
- Complete ANSYS analysis of D4, including a tolerance analysis to verify closure of the yoke gap under all conditions. If a yoke gap is possible, evaluate its effect on field quality.
- Consider making the two prototypes with wire from two different manufacturers.
- Proceed with design of components not affected by the outcome of these studies.

Action items to be addressed before final design of production magnets

- Identify all interfaces to these magnets, develop interface specifications, pass them through the US LHC change control system and enter them into the CERN LHC configuration control system.
- Make electrical and cryogenic schematics for the RF straight section magnet system and for D2 and the relevant parts of the adjacent DFB and cryogenic service module.
- Specify the D3/D4 powering scheme including the maximum trim current required to match their strengths, and enter them in the LHC powering database.
- Consider the CERN high current bus as the default design for the main dipole and quadrupole through buses in D4a and D4b.
- Evaluate field quality impact of different powering of the D2 apertures by up to 0.4 T at 7 TeV and up to 0.09 T at injection.
- Evaluate the field quality of D2 at its (very) low injection field.
- Consider how wire from different manufacturers should be sorted among the different magnet types.

- Consider modification of the RHIC-type yoke laminations to improve the field quality at high field, if this offers advantage for D1 where the best field quality is required under collision conditions. Evaluate whether iron tuning shims within the body of the yoke could be used for field quality correction at high field.
- Evaluate peak voltages and temperatures when 8 apertures of the D3-D4 system are powered in series without diode isolation if the quench heaters act asymmetrically.
- Consider use of standard LHC arc dipole end dome castings for D2 and D4.
- Evaluate alignment stability during shipping and the possible need to re-measure the magnets at CERN.
- Work with the CERN cryogenics group to optimize the cryogenic design and the specifications of the valve boxes that feed the BNL-built dipoles.
- Evaluate whether or not the coil can be guaranteed to stay bathed in sufficient liquid in the presence of beam-induced heating and with the coil "sealed" by phenolic spacers or ground plane insulation.
- Evaluate if a scheme in which the liquid level in the magnet is such that there is a gas "bubble" only at the top at the up-hill end -- that is, that the liquid level is well above the top of the magnet at the down-hill end -- is workable.
- Consider re-arranging the order of fabrication of single- and twin-aperture cold masses to allow time between the prototype tests and beginning of production to react to the results of the tests.

Attachment 1

BNL LHC Dipole Magnet Program
Conceptual Design Review
July 16, 1998

Draft Agenda

Introduction, IR layout & magnet parameters - E. Willen	9:00-9:30
Design Overview - S. Plate	9:30-10:00
Field Quality Criteria - J. Wei	10:00-10:20
Break 10:20-10:40	
Magnetic Designs - A. Jain	10:40-11:40
Magnetic Testing/Acceptance - P. Wanderer	11:40-12:00
Cryogenics - K.C. Wu	12:00-12:30
Lunch 12:30-13:30	
Cold Mass Mechanical Design - J. Schmalzle	13:30-14:15
Structural Analysis - M. Anerella	14:15-15:00
Issues & Summary - S. Plate	15:00-15:30
Discussion & Action Items	15:30-16:00

Attachment 2

Charge to BNL LHC Dipole Conceptual Design Review

This review covers all of the dipoles that BNL will provide for the LHC, which are

D1	single aperture interaction region beam separation dipole
D2	twin aperture interaction region beam separation dipole
D3a/b	twin aperture RF region beam separation dipoles of two different aperture made of two magnets in one cryostat
D4a/b	twin aperture RF region beam separation dipoles of two different aperture spacings (one cold mass)

It will concentrate on the cold mass design and the R&D program, but also consider the cryostat and cooling system designs, which are at an earlier stage of development..

The review committee should evaluate for each of the magnet types and for the program as a whole if the specifications and requirements (magnetic, cryogenic, physical, interface, etc.) are adequately defined, if the chosen designs are likely to meet the requirements in a cost-effective way, if the design aspects requiring prototype construction or other R&D have been properly identified and if the planned R&D program is adequate to address these issues.